Wind Tunnel Study and Uplift Analysis of Geosynthetic Covers

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ABSTRACT

Geosynthetic covers, including the exposed geomembrane cover and engineered turf cover, have been used as alternatives to conventional soil-geosynthetic covers for temporary and final closure of landfills and other waste containment facilities. Because the geomembrane component in geosynthetic covers is not overburdened with a soil layer, uplift of geomembrane due to wind loads is of a concern in the design and construction of such covers. A wind tunnel study was performed to evaluate performance of an exposed geomembrane cover and the ClosureTurf engineered turf cover under wind loads on small-scale test models that were built to simulate a landfill cross section. The wind tunnel test results are presented in the form of dimensionless wind pressure coefficients. An example calculation of the maximum wind uplift pressure on the engineered turf cover is presented.

INTRODUCTION

Landfill covers have been used to protect human and the environment from exposure to the waste. A typical landfill cover prescribed by the federal and state solid waste management regulations in the USA consists of, from bottom to top, a geomembrane barrier layer, a geocomposite drainage layer, and protective and vegetative soil layers. Geosynthetic covers, including the exposed geomembrane cover and engineered turf cover (e.g., ClosureTurf), have been used as alternatives to conventional soil-geosynthetic covers for temporary and final closure of landfills and other waste containment facilities (SWANA 2017).

The exposed geomembrane cover consists of only a geomembrane barrier layer. It eliminates the issues of veneer-type slope instability and soil erosion associated with the prescriptive soil covers. However, since the geomembrane is directly exposed to the environment, it is vulnerable to ultraviolet (UV) damage that limits the design life of the exposed geomembrane cover (Gleason et al. 2001). The engineered turf cover utilizes an engineered synthetic turf layer infilled with sand to cover the underlying geomembrane and protect it from UV degradation (Zhu et al. 2019). Since its first installation in 2009, the engineered turf cover has been increasingly used to close municipal solid waste (MSW) landfills, industrial waste landfill and coal combustion residuals (CCR) impoundments and landfills (Abreu R.C. and Franklin J. 2014, Saindon 2019, O'Malley et al. 2019).

Field observations have shown that the exposed geomembrane can be uplifted by wind. Giroud et al. (1995) summarized the study by Dedrick (1973), where wind tunnel tests were conducted on a reduced-scale test model that simulated an empty reservoir. Based on the published wind tunnel test results, Giroud developed the suction factors for the design of exposed geomembrane cover against wind uplift. A method was also presented to calculate the maximum allowable wind velocity for an exposed geomembrane cover when it is not uplifted and the tension and strain of the geomembrane when it is uplifted. The method was later revised by Zornberg and Giroud (1997) to incorporate the influence of slope inclination and a more accurate expression of the tension-strain relationship of geomembrane.

Recently a wind tunnel study was performed by the authors to evaluate performance of the engineered turf cover under wind loads. Small-scale test models were built to simulate a landfill cross section with a top deck and two side slopes. The models were first covered with the geomembrane to simulate the exposed geomembrane cover. The engineered synthetic turf layer was added later to simulate the engineered turf cover. This paper summarizes the wind tunnel test program and presents the test results for both the exposed geomembrane and engineered turf covers.

WIND TUNNEL TEST SETUPS

The wind tunnel study was carried out between 2018 and 2020 in the Aerodynamic and Atmospheric Boundary Layer (AABL) Wind and Gust Tunnel located in the Department of Aerospace Engineering at Iowa State University, Ames, Iowa. The purpose of the study was to investigate wind performance of the ClosureTurf engineered turf cover and establish wind pressure distribution profiles through model testing. These profiles can be used to evaluate wind loads, especially wind uplift pressures acting on the engineered turf cover.

Four test models were constructed with different sizes to simulate a typical landfill cross section that had a side-slope of 3 Horizontal to 1 Vertical (3H:1V) on one side, a flat top deck, and a side-slope of 4H:1V on the other side. The heights of the models varied from 0.15 m (0.5 ft) to 0.46 m (1.5 ft) and the widths varied from 0.46 m (1.5 ft) to 0.76 m (2.5 ft). Each model had two different slopes allowing rotation in the wind tunnel to test two different windward conditions. A velocity probe was used to record point-wise measurements of the upstream wind velocity. Pressure taps were used to measure wind pressures at fifteen locations along the model surface. The pressure taps were connected by flexible vinyl tubes to a pressure scanner module, where data were recorded. The geometry of one of the test models is shown in Figure 1 along with a photo showing the model inside the wind tunnel. Figure 2 illustrates the distribution of measurement points.

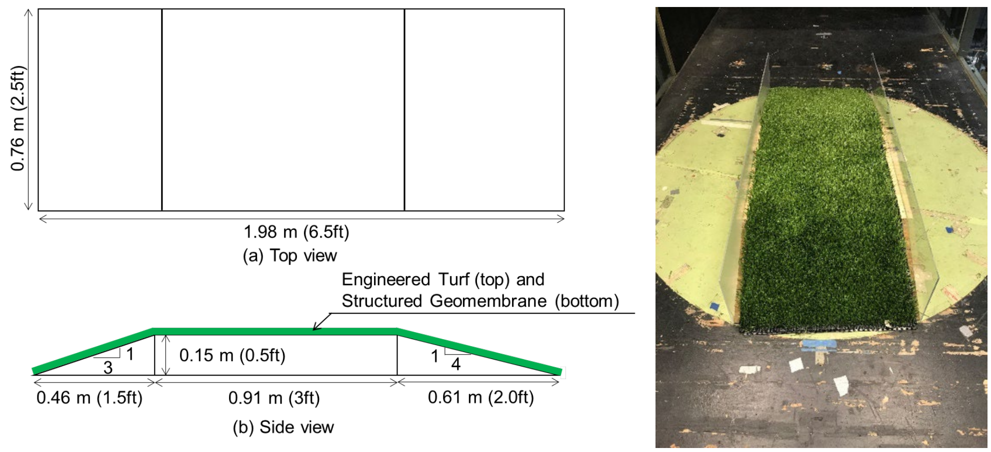

Figure 1. A wind tunnel test model
(left - model geometry; right - photo of model inside wind tunnel).

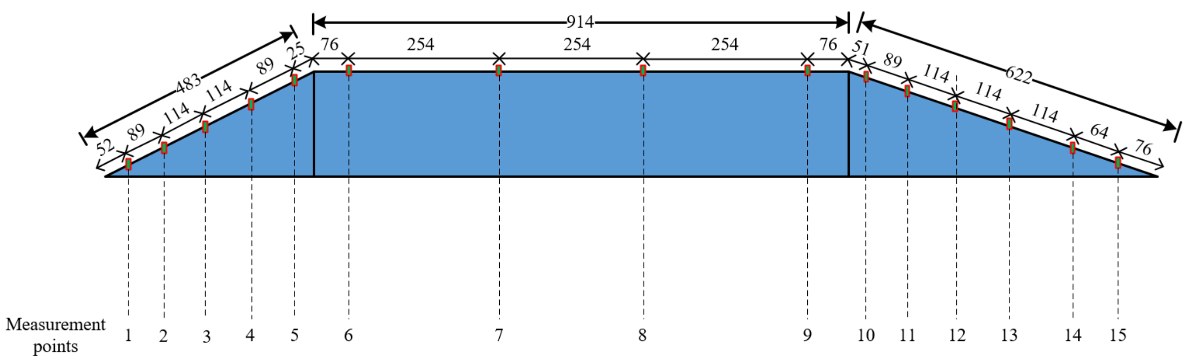

Figure 2. Distribution of wind pressure measurement points
(dimension units are in mm).

The study included tests of both the exposed geomembrane and engineered turf covers. Two types of exposed geomembranes were tested, including a 40-mil (1-mm) thick high-density polyethylene (HDPE) smooth geomembrane and a 50-mil (1.3-mm) thick HDPE structured geomembrane with rough “studded” surface. The engineered turf cover was tested with the engineered synthetic turf layer placed on the 50-mil HDPE structured geomembrane with rough “studded” surface. The geomembrane and engineered turf covers were fixed to the model base in order to measure the wind pressures. No sand infill was applied into the engineered turf during the tests.

WIND PRESSURE COEFFICIENT

The wind pressure coefficient is denoted as C_p and defined as follows (Giroud et al. 1995, Zheng et al. 2020):

$$C_p = \frac{\Delta P}{0.5\rho U(H)^2} \qquad [1]$$

where, ΔP, psf, is the difference between the pressure on the surface of the model and the static pressure of the upstream flow inside the wind tunnel, which is a function of the wind speed in the tests; ρ is the air density (ρ = 0.0024 slug/ft^3 at 15ºC and sea level); and U(H) is the upstream mean wind speed at a height equal to the height of the top of the model, ft/s, with H being the height of the model, ft. A positive value of C_p corresponds to the wind load acting toward the surface (i.e., downward pressure) and a negative value of C_p corresponds to the wind load acting away from the surface (i.e., uplift pressure).

The mean wind speed profile upstream of the model was determined by measuring mean wind speeds at several elevations from the wind tunnel floor. The Power-Law (Peterson and Hennessey 1978) is used for modeling the mean wind speed profile upstream of the test models:

$$\frac{U(z)}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \qquad [2]$$

where, Z is the height above ground; Z_{ref} is the reference height taken as z = H (i.e., at the top of slope model); U_{ref} is the mean wind speed at the reference height taken as U(H); U(z) is the mean wind speed at elevation z; and α is the Power-Law exponent that depends on the terrain over which the wind develops. The value of α was determined as 0.14. Figure 3 shows an example of the measured wind speed profile and the power-law curve fit using α equal to 0.14.

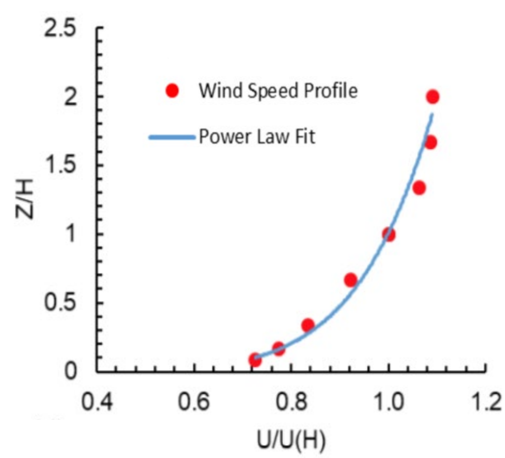

Figure 3. Measured wind speed profile and power-law curve fit (α = 0.14).

A number of test cases were conducted based on combinations of test model, cover type, and wind direction. For each test case, the model was tested for 2 to 3 wind speeds ranging from approximately 5.3 to 22.3 meters per sec (m/s) or 12 to 50 miles per hour (mph). At each wind speed 2 to 3 data runs were taken, resulting in a total of 4 to 9 data sets for each test case. The measured surface pressures were normalized by wind speeds and reported as the dimensionless pressure coefficients according to Eq. 1. The pressure coefficients were found to be consistent and did not show significant variations with respect to the magnitude of wind speed or model sizes. The average C_p values were calculated from the 4 to 9 data sets and reported as the final C_p values for each test case.

WIND TUNNEL TEST RESULTS

Exposed Geomembrane Cover. The measured wind pressure coefficient profiles are plotted in Figure 4 for the smooth and rough geomembranes with wind blowing toward the 3H:1V slope and Figure 5 for the smooth geomembrane with wind blowing toward the 4H:1V slope. In the remainder text of this paper, C_p values are reported as absolute values and the context of the value (i.e., downward or uplift pressure) is made clear. The test results indicate that:

- The windward side slope (i.e., the slope facing toward the wind) was initially under downward pressure. The rest of the model was under uplift pressure.
- The maximum uplift pressures occurred near the slope crests with peaks on both the windward and leeward (i.e., the slope facing away from the wind) side slopes.
- For the smooth geomembrane:
    - When the 3H:1V was on the windward side, the measured maximum uplift C_p values were 1.24 near the crest of the 3H:1V slope and 1.15 near the crest of the 4H:1V slope;
    - When the 4H:1V slope was on the windward side, the measured maximum uplift C_p values were 1.13 near the crest of the 4H:1V slope and 1.34 near the crest of the 3H:1V slope; and
    - The measured maximum uplift C_p value for 3H:1V slope is approximately 10% greater than that for 4H:1V slope.
- For the rough "studded" geomembrane:
    - For the case of the 3H:1V slope on the windward side, the three models with different sizes yielded reasonably consistent results, indicating that the measured C_p values can be considered independent on the model scale. The average measured maximum uplift C_p values were 0.60 near the crest of the 3H:1V slope and 0.40 near the crest of the 4H:1V slope; and
    - The measured uplift C_p values were significantly lower than those for the smooth geomembrane, indicating that wind uplift pressure decreased as the surface roughness of the cover increased.

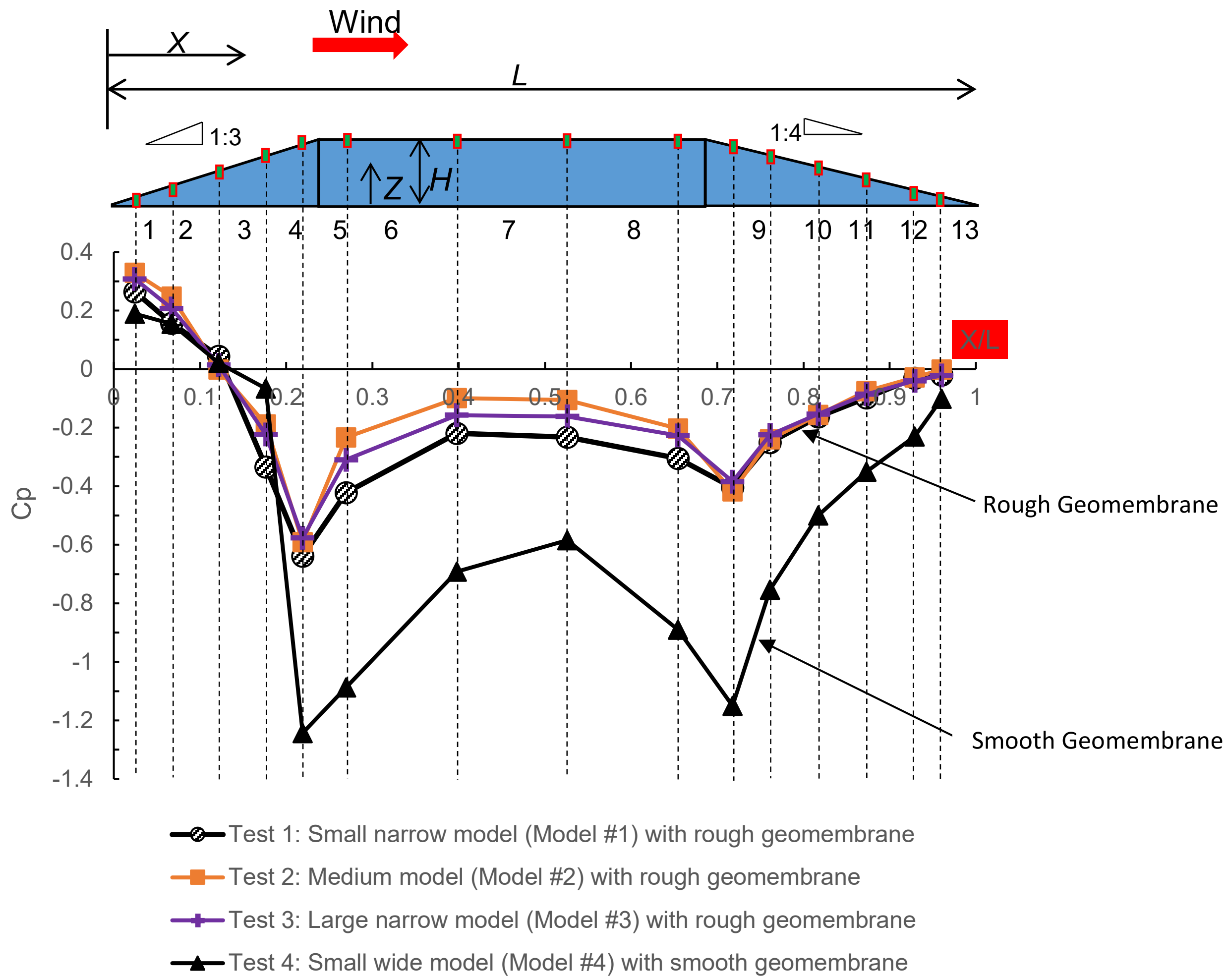

Figure 4. Measured C_p profiles of exposed smooth and rough geomembrane covers. (wind toward 3H:1V slope)

Giroud et al. (1995) proposed a solution of wind-generated uplift coefficient for geomembrane, which was denoted as the suction factor for design of any slope based on the critical leeward slope. In this solution, the suction factors were recommended to be 1.0 in the top deck of a slope, 0.85 in the top third of a slope, 0.70 in the middle third of a slope and 0.55 in the lower third of a slope. The average suction factor on a slope was 0.70. This solution was later modified (Perera et al. 2011), where the suction factors were decreased by 23% based on field performance of exposed geomembrane covers (e.g., the maximum suction factor was decreased from 1.0 to 0.77 in the top deck of a slope). It should be noted that neither of these solutions accounted for variation in surface roughness of geomembrane nor the slope ratio. With respect to the maximum uplift pressure coefficient, both the original and modified solutions by Giroud and Perera are within the range of coefficients measured in this study. The values of the original solution are closer to these measured for the smooth geomembrane and the values of the modified solution are closer to these measured for the rough, “studded” geomembrane.

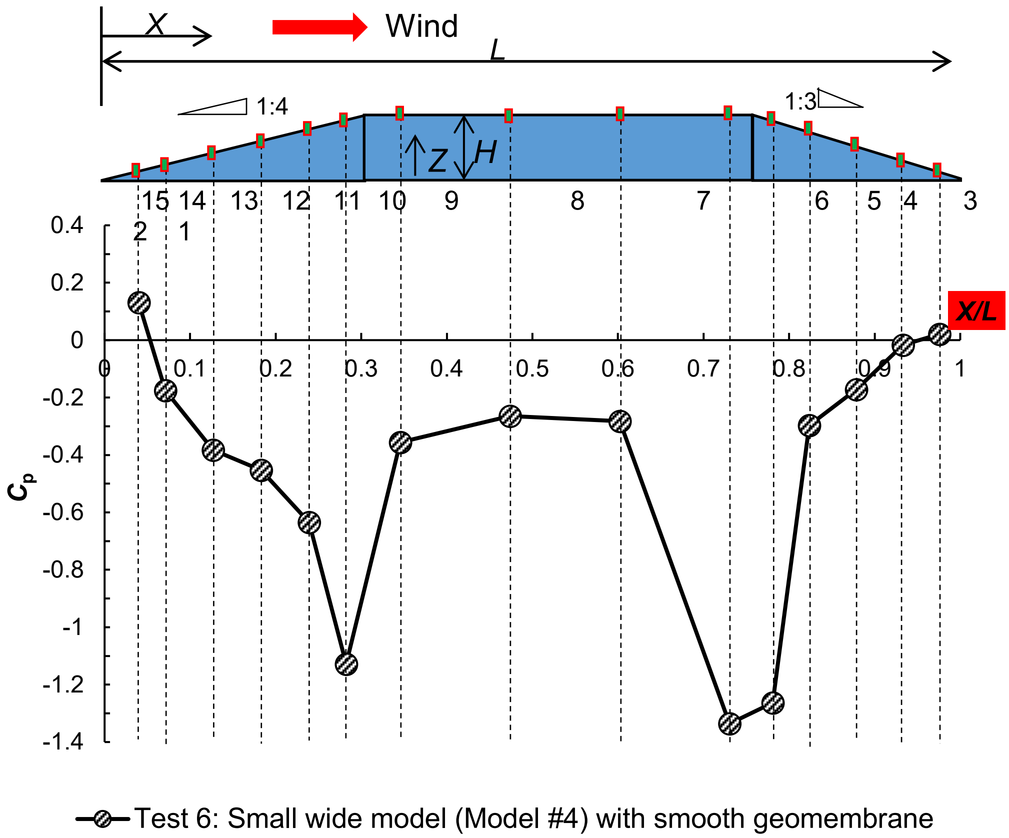

Figure 5. Measured C_p profiles of exposed smooth geomembrane cover. (wind toward 4H:1V slope)

ClosureTurf Engineered Turf Cover. The measured wind pressure coefficient profiles are plotted in Figure 6 for the engineered turf cover with wind blowing toward the 3H:1V slope and Figure 7 with wind blowing toward the 4H:1V slope. The test results indicate that:

- Approximately half of the windward side slope was under downward pressure and the rest of the model was under uplift pressure.
- The maximum uplift pressures occurred on the top near the crest of the windward side slope. The second peak near the crest of the leeward side slope was much smaller than that near the crest of the windward side slope.
- For the case of the 3H:1V slope on the windward side, the four models with different sizes yielded reasonably consistent results, indicating that the measured C_p values can be considered independent on the model scale. The average measured maximum uplift C_p value was 0.38 near the crest of the 3H:1V slope and 0.25 near the crest of the 4H:1V

slope. These values are approximately 65% of those for the rough, "studded" exposed geomembrane cover and 25% of those for the smooth exposed geomembrane cover.

- When the 4H:1V slope was on the windward side, the measured maximum uplift C_p values were 0.29 near the crest of the 4H:1V slope and 0.18 near the crest of the 3H:1V slope, which are lower than those for the 3H:1V slope.

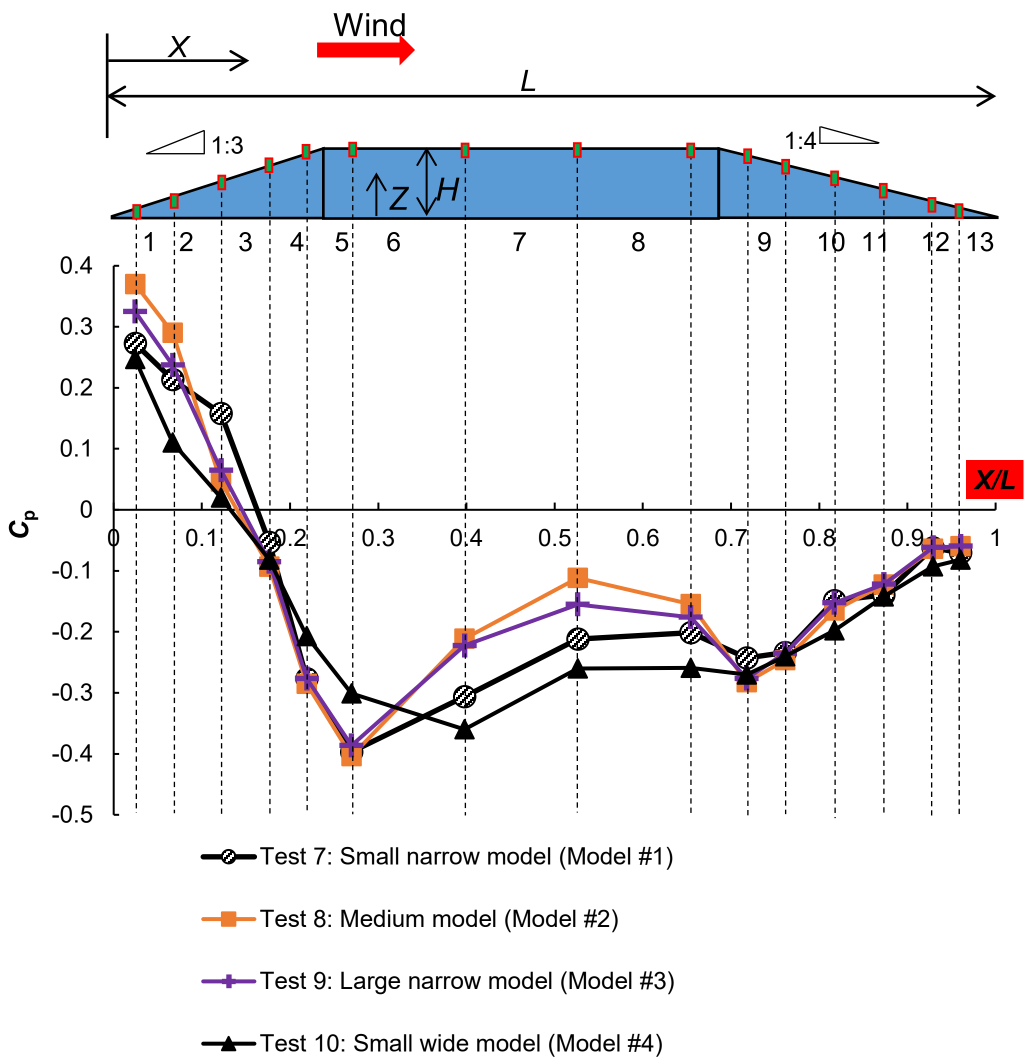

Figure 6. Measured C_p profiles of engineered turf cover.
(wind toward 3H:1V slope)

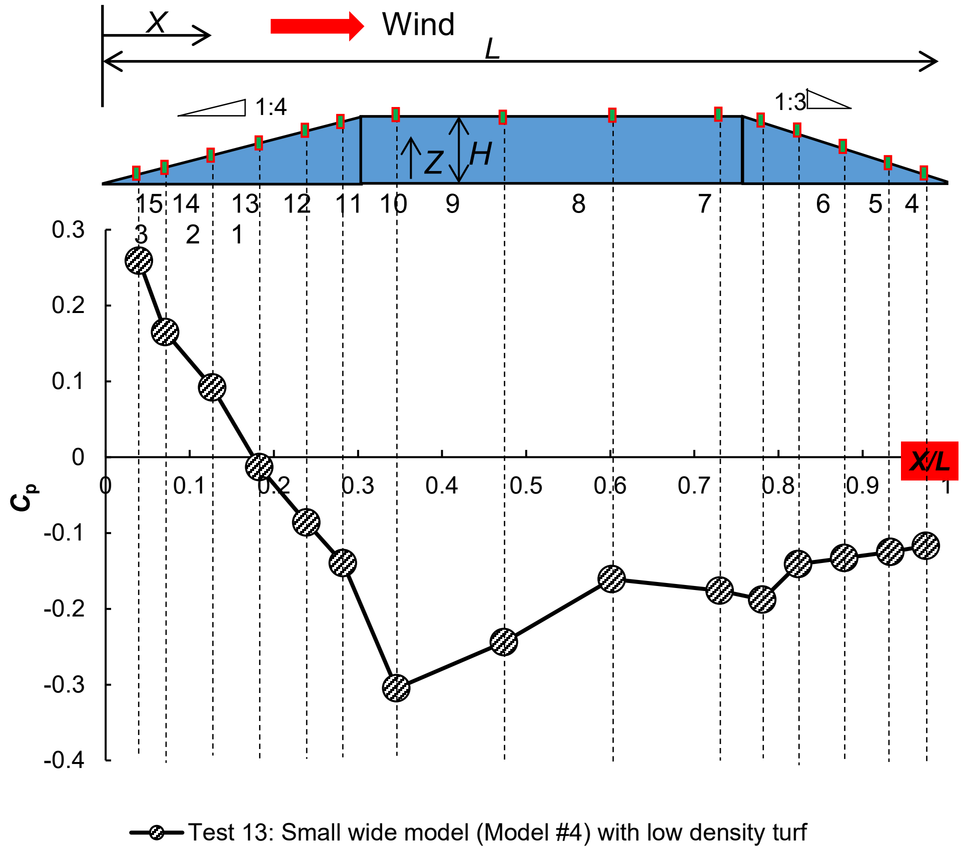

Figure 7. Measured C_p profiles of engineered turf cover. (wind toward 4H:1V slope)

Summary. The measured maximum wind uplift pressure coefficients are summarized in Table 1 below.

Table 1. Measured maximum wind uplift pressure coefficients. (compared with Giroud's solutions)

Cover Type	3H:1V Slope (This study)	4H:1V Slope (This study)	Giroud's Solution	Modified Giroud's Solution
Smooth Exposed Geomembrane Cover	1.24	1.13	1.0	0.77
Rough, "Studded" Exposed Geomembrane Cover	0.60	N/A		
ClosureTurf Engineered Turf Cover	0.38	0.29	N/A	N/A

EXAMPLE WIND UPLIFT CALCULATIONS OF ENGINEERED TURF COVER

A hypothetical landfill is located in Ames, Iowa. The landfill is 50 ft high with a 3H:1V slope. The design wind speed was assumed to be 83 mph (or 121.73 ft/s) for Ames, Iowa based on ASCE 7-16 (https://hazards.atcouncil.org/#/). This corresponds to the 3-second gust speed at 32.8 ft (or 10 m) elevation in open terrain, U_3(32.8ft) or U_3(10m), with a mean recurrence interval (MRI) of 25 years.

Li et al. (2020) presented a detailed study on using the 3-second gust speed divided by a conversion factor to account for the uplift resistance provided by the temporary suction developed below the geomembrane as it is being uplifted. The conversion factor ranges from 1.23 to 1.75 based on varying tropical cyclone conditions and averaging periods (1 minute to 1 hour) (Harper et al. 2008). An example calculation was presented in the paper that used the 60-minute (i.e., hourly) average wind speed in the design of the anchor system for an exposed geomembrane cover. To obtain the 60-minute average wind speed, the 3-second gust speed was reduced by a conversion factor of 1.75 that corresponded to an in-land, roughly open terrain.

For the example calculation presented in this paper, the mean hourly wind speed at 32.8-ft (or 10-m) elevation, U(32.8ft) or U(10m), is conservatively calculated from the 3-second gust speed, U_3(32.8ft), using a factor of 1.5 for an open terrain (Vickery and Skerlj 2005):

$$U(32.8\text{ ft}) = U_3(32.8\text{ft}) / 1.5 = 121.73\text{ ft/s} / 1.5 = 81.15\text{ ft/s}$$

Using U(32.8 ft) as the reference, the mean hourly wind speed at top of the landfill, U(H) with H = 50 ft, is calculated using Eq. 2:

$$\frac{\mathrm{U(H)}}{\mathrm{U(32.8\ ft)}} = \left(\frac{\mathrm{H}}{32.8\ \mathrm{ft}}\right)^{0.14}$$

$$\frac{\mathrm{U(H)}}{81.15\ \mathrm{ft/s}} = \left(\frac{50\ \mathrm{ft}}{32.8\ \mathrm{ft}}\right)^{0.14}$$

$$\mathrm{U(H)} = 86.08\ \mathrm{ft/s}$$

The maximum mean wind uplift pressure is calculated according to Eq. 1 using the maximum uplift C_p value of 0.38 for a 3H:1V slope:

$$P_{max} = C_p \times 0.5\rho U(H)^2 = 0.38 \times 0.5 \times 0.0024 \times 86.08^2 = 3.4\ \mathrm{psf}$$

The weight of engineered turf cover (e.g., ClosureTurf) per unit area is about 5.4 psf with a 0.5-in thickness of sand infill. The factor of safety (FS) for wind uplift is calculated to be 1.6 (i.e., 5.4 psf/3.4 psf) for the assumed landfill cross section. Therefore, the engineered turf cover is considered to have adequate wind resistance under the design wind loads. If a higher design wind speed is used and the maximum uplift pressure exceeds the weight per unit area of engineered turf, further calculations may be required to evaluate whether the tension induced by the wind loads is acceptable; or thicker sand infill, anchor trenches or other means can be used to further secure/ballast the material. Note that these additional measures would only be needed in those portions of the installation where the predicted FS is deemed not adequate.

CONCLUSION

The wind tunnel study is presented that was carried out to evaluate wind uplift of the exposed geomembrane and engineered turf landfill covers. The wind tunnel tests were performed on scaled slope models with different slope ratios, surface roughness, and wind speeds. The test results showed that:

- The wind-induced uplift pressure is mainly affected by the surface roughness of the cover. The measured maximum uplift pressure coefficient decreases as the roughness increases from smooth geomembrane to rough “studded” geomembrane to rougher engineered turf. The measured maximum uplift pressure coefficient values for the engineered turf cover are approximately 60% of those for the rough, “studded” exposed geomembrane cover and 30% of those for the smooth exposed geomembrane cover, which demonstrates the effect of the engineered synthetic turf layer on protecting the underlying geomembrane from wind uplift.
- The wind pressure is also affected by the slope ratio. Compared with a 4H:1V slope, the measured maximum uplift pressure coefficient values of a 3H:1V slope increase by approximately 10% and 30%, respectively, for the smooth exposed geomembrane and engineered turf covers; and
- The distributions of the measured wind pressure coefficients have been found to be reasonably consistent with respect to varying wind speeds and model sizes, which confirms that the dimensionless coefficients measured on small-scale models tested under wind speeds in the wind tunnel facility can be scaled up and used for full-scale landfill cross section subject to higher design wind speeds.

The wind pressure coefficient profiles presented in this paper can be used to evaluate whether the geosynthetic landfill covers, i.e., the exposed geomembrane and engineered turf covers, have sufficient resistance against wind uplift under the selected design wind speed.

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